Inventory Optimization for Mercurius Shipping Group's Container-Crane Vessels

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Abstract

Mercurius Shipping Group invested in two container-crane vessels which are able to load and unload cargo to and from its own holds. Due to their unique feature, the crane, failure of these vessels results in large financial consequences. Previous experience showed that these costs could be mitigated with easily/timely available spare-parts. The main aim of this study was to increase the reliability of Mercurius Shipping Group's container-crane vessel MKS Mercurius by proposing an optimized spare-part inventory. Subsequently, by doing so, reducing the total costs of operating and maintaining the vessel and ensuring profit maximization for MSG. Cost models have been developed to quantify the reduction in financial risk of failures, by having spare-parts directly available, and to determine the costs of keeping a spare-part inventory. As a result a list of spare-parts is proposed based on a comparison between the reduced failure impact/costs (benefit), with a spare-part in inventory, and the corresponding annual inventory costs. The results showed that a cost-effective improvement to vessel reliability, due to a decrease in vessel downtime, can be achieved with direct availability of spare-parts kept in inventory. Currently equipped with two container-crane vessel the optimum inventory consists of 13 components, requiring an investment of €50,000 and leading to an improvement to the vessels financial performance of €13,000 per year. In case MSG decides to relocate one of the container-crane vessels, the impact of failure increases. In this case the recommended inventory should be expanded to 28 components, requiring an investment of €137,000 and leading to an improvement to the vessels financial performance of €55,000 per year.

Key words: Inland Shipping; Inventory; Spare-Parts; Maritime Crane, Benefit/Cost Assessment, Failure Impact.

1 Introduction

Mercurius Shipping Group (MSG) consists of collaborations of inland shipping entrepreneurs. They develop, build, operate, charter and invest in a variety of inland barges [8]. MSG's strategy is investing in vessels with unique features, which distinguishes them from conventional inland vessels and provide added value due to these properties. For this reason they invested in two container-crane vessels which are able to load and unload cargo in remote areas, ports without crane capacity and deliver directly to companies located on inland rivers. The container-crane vessels offer container pick-up and delivery services mainly to clients located in the Port of Rotterdam area. The idea behind this mode of transport is to fit the needs of their clientele by transporting containers in a fast, sustainable and efficient manner from large seaports to their remote locations, and while doing so reducing road congestion in the port.

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Reliability of these barges is an important quality for the operational management. This is partly due to the fact that the crane mounted on these barges is an unique feature for inland barges, which means there are no comparable vessels operating in the area and no immediate replacement is available for these vessels in case of failure. As a consequence, failure results in large revenue losses and other high financial consequences related to alternative pick-up and delivery solutions for containers located at clients. For MSG this was reflected in 2016, when both crane barges were unavailable for a two week period. The first crane barge ('MKS Mercurius') had a scheduled docking to replace the crane cylinders; and the second barge ('MKS Transferium') experienced an equipment malfunction regarding the crane, of which the effects could have been mitigated when parts would have been easily available. Due to long delivery times for Liebherr's crane parts, multiple weeks, the technical department was forced to find alternative solutions in order to fix these problems. During this two week period these problems had a large impact on both revenue and costs, which were not solely repair costs but also large costs related to loss of business and lost opportunities.

The total loss of business, including estimated revenue losses and recovery costs (loss of revenue in the weeks(s) after the failure had been restored), are estimated at approximately €100,000 - €130,000 (M. Kleijn, personal communication, April 7, 2017). These costs would have been mitigated with easily/timely available spare-parts. Along with the high financial consequences, long downtime of the crane barges may also incur reputational damages to MSG and affect client trust. This makes reliability an important attribute for the crane barges to maintain/improve their position in the market and to be able to keep client trust.

Due to the mentioned importance of reliability for these vessels, MSG would like to explore the possible mitigation of risk (of failure) by holding spare crane components; and ultimately set up an optimized spare-part inventory for critical systems of the MKS Mercurius container-crane barge. The main aim of this study is to increase the reliability of Mercurius Shipping Group's container-crane vessel MKS Mercurius by proposing an optimized spare-part inventory. Subsequently, by doing so, reducing the total costs of operating and maintaining the vessel and ensuring profit maximization for MSG. To this end, the main research question is formulated as: *For which crane components/parts will keeping a spare-part inventory result in a cost-effective improvement of the reliability for the container-crane vessel MKS Mercurius?*.

The present research article is organized as follows: Section 2 presents the research design and describes the methods used to define this approach. The obtained results are analysed in Section 3, and in Section 4 conclusions are drawn and inventory recommendations for MSG are described.

2 Methods & Related Literature

The research question is answered through the development of cost models to quantify the reduction in financial risk of failures, by having spare-parts directly available, and to determine the costs of keeping a spare-part inventory. Due to the fact that MSG is currently equipped with two container-crane vessel, availability of the second barge MKS Transferium in case of failure of the MKS Mercurius has an effect on the impact of failure. Since, in the future, MSG might want to relocate one of the container-crane vessels, the failure impact is determined for both: (1) MKS Mercurius taking into account availability of the MKS Transferium in case of failure, and (2) MKS Mercurius as MSG's single container-crane vessel. As a result a list of spare-parts is proposed based on a comparison between the reduced failure impact/costs (benefit), with a spare-part in inventory, and the corresponding annual inventory costs. A schematic representation of the research approach is presented in Figure 1.

In this section the followed methods and literature used to define the research approach is presented. Each section describes the methods and literature for one of the phases of the research (Fig. 1).

2.1 System Analysis

In order to ultimately propose a spare-part inventory it is first important to understand what systems and components the cargo handling gear consists of. For this reason an analysis of the crane system and its failure mechanisms is performed.

First a component breakdown is composed where all systems and parts related to the vessels cargo handling gear are defined. The likelihood of failure of a component in a specific time-frame is represented by its failure rate or (annual) failure probability. The failure rate (λ) is defined as the relative frequency at which an engineered system or component fails, expressed in failures per unit of time, and is highly used in reliability engineering [2]. The probability of an occurrence - or the probability of a certain failure rate - is mathematically described by defining a suitable probability distribution. There are different suitable distributions available, such as the negative exponential distribution, the normal distribution, and the Weibull distribution. Of these distributions the negative exponential distribution is the most used distribution in reliability/availability studies, and is used for most practical applications [5,2,4,11]. This method makes use of one single parameter, the average life expectancy (η) of the component, with which the failure probability at time t can be determined:

$$f(t) = \frac{1}{\eta} e^{-(\frac{1}{\eta})t} \quad (1)$$

Furthermore, this method has no memory of prior usage. Specifically, within any fixed period of usage, the probability of failure is the same. Therefore this distribution provides an identical failure probability for the component (in % per year) during its entire useful (design) life. Due to its simplicity and limited amount of required failure data this distribution is considered most suitable for this application.

With the failure probabilities of each single component known, a failure analysis can be executed to determine the availability/reliability of the container-crane vessel. With a failure analysis the root causes of malfunctioning systems and the probability of this failure occurring can be determined. The most used method to conduct a failure analysis in reliability engineering is by Fault Tree Analysis (FTA) [1,9,11]. Fault Tree Analysis is a top-down approach where an undesirable event is identified as the top event in the tree and the potential causes that could lead to the undesirable event are identified as branches below. FTA uses Boolean algebra

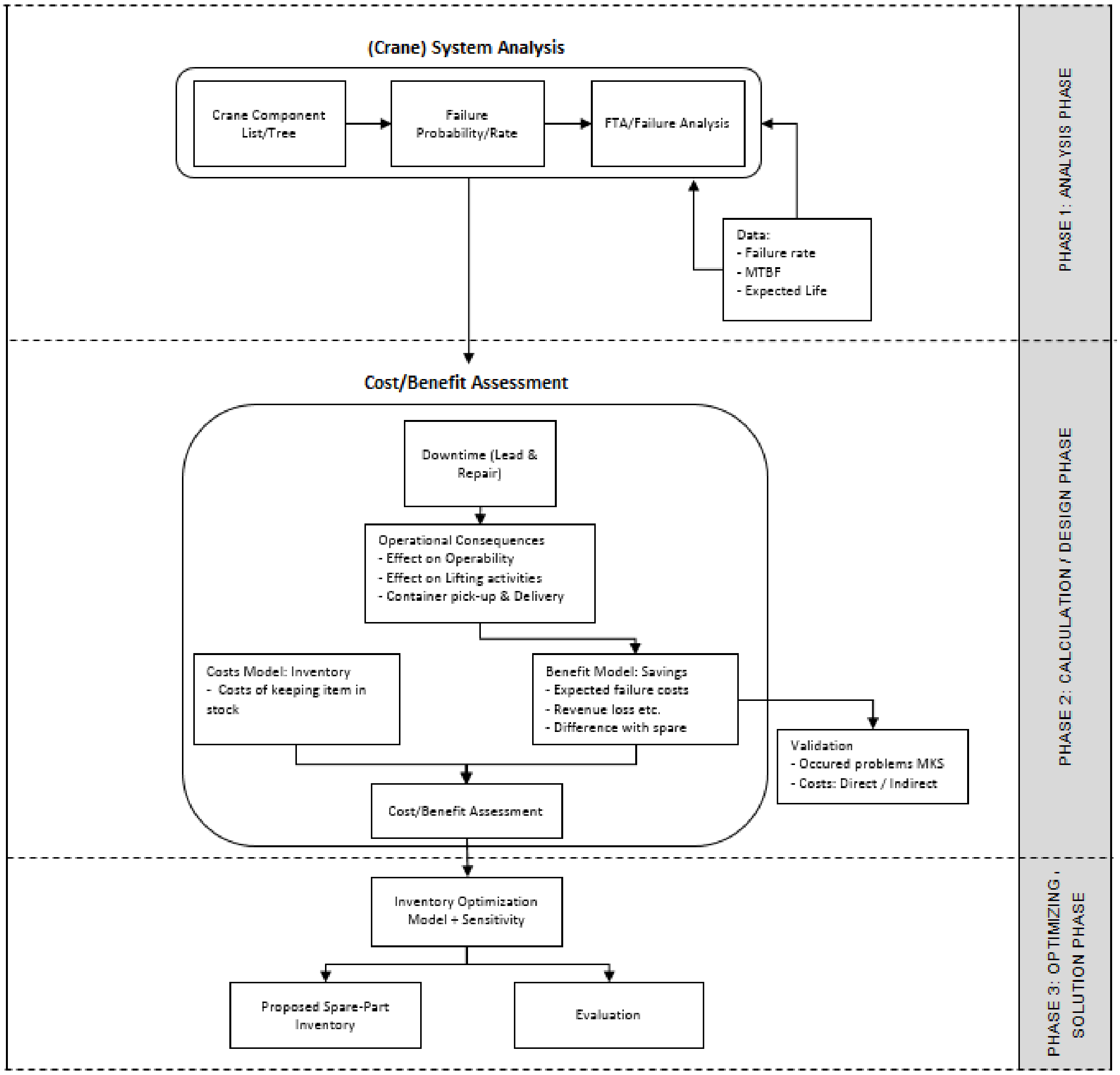

Fig. 1. Research Approach

(AND gates and OR gates) in a graphical representation to show the logical interrelationships between the initiating event (component failure) in a branch to other branches and the top event. If the failure rate is available for all of the initiating events (component failures) in the fault tree, results (failure probability, reliability, etc.) can be calculated for the top event and each of the branches [10,12,11]. Using for an AND gate:

$$P_{sys}(t) = P_a \times P_b \times P_c \times .... \times P_n \tag{2}$$

and for an OR gate:

$$P_{sys}(t) = 1 - (1 - P_a) \times (1 - P_b) \times (1 - P_c) \times .... \times (1 - P_n) \tag{3}$$

FTA is a widely used reliability tool and is suitable for different applications. [7] presented an application of FTA on gearboxes of commercial vehicles, [13] used it to determine criticality of systems of an offshore vessel to improve its maintenance strategy, [6] used it to model reliability for a marine main engine and [4] used it to identify criticality and reliability of ship machinery in a study on unmanned shipping. The FTA method is used in this research, since it: focuses on interrelationships between component failures and vessel functions; it provides a graphical, structured and easily understandable image; and it highlights the important elements of components related to system failures. Alternative methods (such as Failure Mode and Effect Analysis) usually require more expertise and are more time-consuming, making them unsuitable for this application.

The system and component breakdown, the fault tree set-up and corresponding Fault Tree Analysis is based on system documentation from the crane manufacturer

Liebherr, based on findings during vessel visits and constructed with the aid of the technical department.

2.2 Cost/Benefit Assessment

Once the systems and components related to the vessels cargo handling gear are defined and the effect of failure of these components on vessel availability is determined, a benefit/cost assessment is made to determine for which components it is cost-effective to store them in inventory. Cost models are developed to quantify the reduction in financial risk of failures (benefit), by having spare-parts directly available, and to determine the costs of keeping a spare-part inventory. As a result a selection of spare-parts is proposed based on a comparison between the reduced failure impact/costs (benefit), with a spare-part in inventory, and the corresponding annual inventory costs. The failure impact (costs) is defined as a function of failure duration, operational consequences, and availability (residual capacity) of the MKS Transferium in case of failure. Input for the benefit model is therefore downtime, or failure durations, and the effects on vessel operations.

Downtime, or the failure duration, is dependent on the lead time of spare-parts and on the duration of component repair/replacement. For simplicity only failure durations in case of complete component replacements are taken into account, which is of most interest when spare-parts are required. Furthermore, with direct availability of spare-parts it is assumed that lead time is completely eliminated. The lead and repair time for each component is based on a combination of (partial) data from suppliers and input from the technical department. Component failures, and resulting failures, have various effects on vessel operations. To determine the effect on operability it is first analysed in which different vessel states or vessel conditions the vessel can be deployed. For example, failure of a component can result in inability to use the crane. In this condition however the vessel can still be used as a conventional barge. Furthermore component failure could lead to restrictions in the use of the crane, with a weight limitation or limited rotation speed. There is a wide spectrum of possible effects which can be related to the vessel condition and duration of the failure. These effects can have an impact on delivery of containers located in the holds, container pick-up from client locations or pick-up and delivery of containers at a terminal. After these consequences on operability are mapped, the fault tree is further expanded to indicate which component failures lead to the derived vessel states. These operational consequences are translated to financial consequences of failure, quantified by total failure costs, and are divided in repair costs and downtime related costs. The repair costs consist of: equipment/yard costs, hire of external personnel, delivery costs, and component price. For the downtime related costs a division is proposed in: opportunity costs, container removal costs, additional planning costs, and business recovery costs. The effect of direct availability of spare-parts on these failure costs (and therefore failure impact) is determined to quantify the potential financial benefit in case of failure:

$$\textit{Potential Benefit} = \textit{Impact without Inventory} - \textit{Impact with Inventory} \quad (4)$$

By multiplying the potential benefit by the annual failure probability of the component an expected annual benefit is determined for keeping an item in inventory:

$$\textit{Annual Benefit} = \textit{Annual Failure Probability} \times \textit{Potential Benefit} \quad (5)$$

Due to the fact that MSG is currently equipped with two container-crane vessel, availability of the second barge MKS Transferium in case of failure of the MKS Mercurius has an effect on the impact of failure. Since, in the future, MSG might want to relocate one of the container-crane vessels, the annual benefit is determined for both: (1) MKS Mercurius taking into account availability of the MKS Transferium in case of failure, and (2) MKS Mercurius as MSG's single container-crane vessel.

Besides the benefits of having a spare-part inventory, which is mainly the elimination of lead time and resulting reduction in failure costs, there are also annual costs related to keeping a spare-part in inventory. These annual inventory costs entail: interest costs; risk costs, including insurance and depreciation; and warehousing costs [3].

Indications for parameters of the costs models are based on data from suppliers, input from the technical department, indications from barge operator MCT Lucassen (subsidiary of MSG), and/or are based on historical performance.

2.3 Inventory Selection & Optimization (Solution)

Inventory selection is based on the outcome of the costs models, which provides a comparison between the benefit of keeping a spare-part inventory and the corresponding annual inventory costs. Leading to a net benefit:

$$\textit{Annual Net Benefit} = \textit{Annual Benefit} - \textit{Annual Inventory Costs} \quad (6)$$

Obviously, when the annual benefits outweigh the annual inventory costs, it is considered cost-effective to store the component in inventory.

Besides the inventory selection, the effect of this selected inventory on vessel reliability and the vessels financial performance is numerically evaluated by Monte-Carlo simulation. Monte Carlo simulation is a mathematical technique that generates random variables for modelling risk or uncertainty of a certain system. By randomly generating the failure probabilities and resulting failures within a year, a distribution can be generated comparing the resulting annual costs (consisting of failure costs and inventory costs) to the frequency of their occurrence. With this distribution the expected annual costs can be determined, leading to a determination in the improvement to the vessels financial result and the increase in vessel availability/reliability.

3 Results & Discussion

This research was intended to increase the reliability of Mercurius Shipping Group's container-crane vessel MKS Mercurius by, exploring the need for and, optimizing a spare-part inventory. Subsequently, by doing so, reducing the total costs of operating and maintaining the vessel, ensuring profit maximization for MSG. Due to the (current) availability of a second container-crane vessel, in case of failure of the MKS Mercurius, an inventory optimization is made for both: (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure; and (2) MKS Mercurius as MSG's single container-crane vessel. The results showed that a cost-effective improvement to vessel reliability, due to a decrease in vessel downtime, can be achieved with direct availability of spare-parts kept in inventory.

This section addresses the outcome of the cost models and Monte-Carlo simulation(s). The effect of inventory on annual costs, vessel reliability and the vessels financial performance is analysed and the resulting inventory composition is discussed.

3.1 Cost Minimization

The effect of inventory on the vessels financial performance is dependent on the selection of components stored in inventory. The resulting optimal, cost-minimizing, level of inventory for both scenarios is shown in Figures 2 and 3. The level of inventory represents the percentage of crane components stored in inventory ranked by the largest individual net benefits. For example, in case of an 30% inventory level, this means that the 30% of components with the largest calculated net benefits are included in the inventory. It can be seen that, by increasing the level of inventory, the failure costs decrease, which is the result of reduced downtime due to the direct availability of spare-parts. On the contrary, for larger inventory levels, the annual inventory costs increase due to an increase in the number (and value) of components stored in inventory. At a certain point the increase in annual inventory costs exceeds the decrease in annual failure costs, resulting in increasing total annual costs and establishing a clear optimum level of inventory.

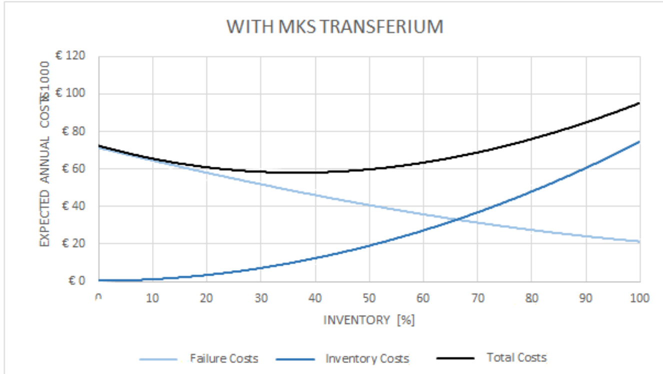

Fig. 2. Distribution of Annual Costs (Failure, Inventory, Total) based on level of Inventory (With MKS Transferium)

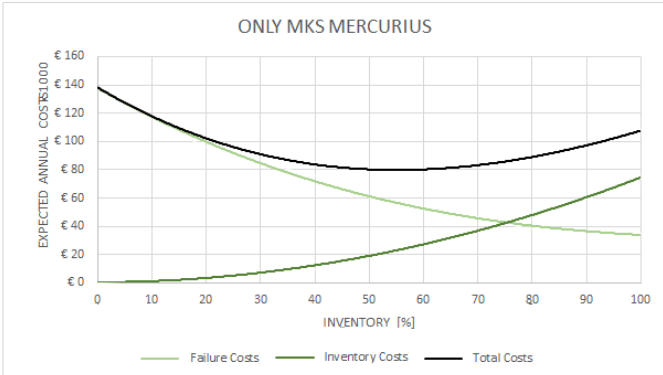

Fig. 3. Distribution of Annual Costs (Failure, Inventory, Total) based on level of Inventory (Only MKS Mercurius)

Furthermore, it can be seen that due to the presence of a second container-crane vessel in case of failure, even without inventory, the expected annual failure costs are significantly reduced. Additionally, in comparison, the reduction of annual failure costs for increasing levels of inventory is also less significant due to the presence of a second container-crane vessel. As a result, for this scenario, the expected annual costs for large levels of inventory ($\geq$70%) exceed the expected annual costs without any inventory and keeping a large spare-part inventory ($\geq$70%) is therefore not cost-efficient. In comparison, for MKS Mercurius as single-acting vessel, these large levels of inventory would still result in an improvement to the vessels financial performance and therefore still yield satisfactory results (not taking into account the required investment).

The optimal level of inventory is equal to $\approx$35% for MKS Mercurius, with availability of MKS Transferium in case of failure; and equal to $\approx$55% for MKS Mercurius as MSG's single container-crane vessel.

3.2 Effect on Vessel Availability/Reliability

The effect of inventory on vessel availability/reliability is also dependent on the selection of components stored

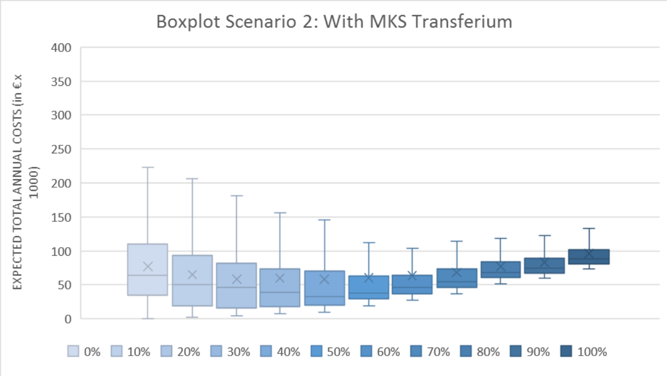

Fig. 4. Distribution and Spread of possible Annual Costs based on level of Inventory (With MKS Transferium)

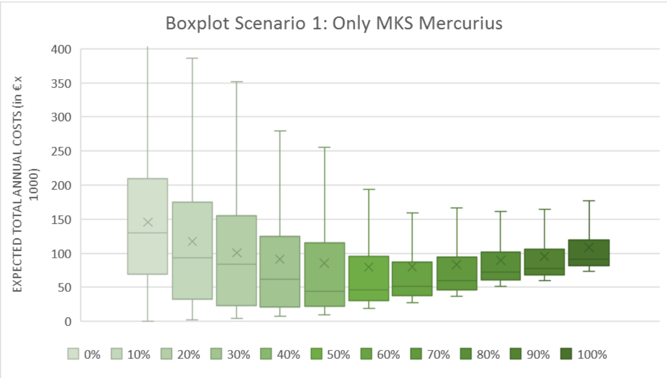

Fig. 5. Distribution and Spread of possible Annual Costs based on level of Inventory (Only MKS Mercurius)

in inventory. Reliability is defined as the ability to consistently perform its intended or required functions. Increasing reliability can thus be achieved by decreasing vessel downtime. The effect of inventory on vessel availability/reliability is evaluated by the distribution and spread of expected annual costs, obtained from the simulations, for different inventory levels. The distribution of annual costs (including failure costs and inventory costs) for both scenarios is visualized with box plots, which are shown in Figures 4 and 5. With these box plots a clear summary of the outcomes (annual costs) for the different levels of inventory is presented. A box plot displays the distribution of data based on the five number summary, consisting of the: minimum, first quartile, median (or second quartile), third quartile, and maximum.

From the box plots (Fig. 4 and Fig. 5), it can clearly be seen that the spread of expected annual costs reduces, as the level of inventory increases. This can be explained by the fact that with more components stored in inventory, the probability of component failures resulting in significant downtime and large failure costs decreases, which means that the resulting annual costs are more concentrated. Thus, this effect is related to vessel availability/reliability and by increasing the level of inventory vessel reliability increases. Vice versa, with decreasing inventory level, reducing the amount of components stored in inventory, the probability of component failures with severe consequences increases and the resulting annual costs are more spread. Thus leading to reduced certainty and a reduction in vessel reliability.

Comparing both scenarios, it can be seen that, even without inventory, the spread of (possible) annual costs with both vessels operating in the same area is significantly reduced (compared to the single vessel scenario). As a result, for MKS Mercurius as MSG's single container-crane vessel inventory leads to a significant improvement to vessel reliability. This means for this scenario the effect on reliability is crucial and the (optimal) amount of components in inventory (expressed by inventory level) increases.

3.3 Inventory Selection(s)

The MKS Mercurius and MKS Transferium both operate in the Port of Rotterdam are, which means, in case of failure of the MKS Mercurius, lifting activities scheduled to be executed by the MKS Mercurius can be taken over by the MKS Transferium. Therefore the scenario related to failure of the MKS Mercurius with availability of a second container-crane vessel is currently most relevant for MSG. The recommended inventory is shown in Table 1, (most of) the components are visualized in Figures 6, 7 and 8. The selected inventory includes 13 components. This inventory requires an initial investment of €50,000, includes €8,500 annual inventory costs, and leads to a reduction of expected annual failure costs of €22,000, which means the annual net benefit is equal to €13,500. As a result the investment is expected to be recouped within a period of approximately 4 years. A larger inventory would require a larger investment and all-though this would lead to a further decrease of failure costs this effect is countered by the increasing annual inventory costs, resulting in an increase in total cost and a smaller net benefit. The increase in inventory would lead to an increase in vessel availability, but since this results in larger costs it is considered a sub-optimal inventory.

In case MSG decides to relocate (or sell etc.) one of the container-crane vessels the effect of direct availability of spare-parts increases, because the financial impact of failure is significantly larger due to the absence of a second crane vessel, able to execute lifting activities. This means for the scenario with MKS Mercurius as MSG's only container-crane vessel inventory becomes more crucial, in order to ensure minimal downtime of the vessel and minimize annual costs. Therefore, when the decision is made to relocate (or sell) the MKS Transferium, MSG should expand MKS Mercurius' spare-part inventory. For this reason a more extensive inventory is recommended, including 28 components (Table 2). This inventory requires an initial investment of €137,000, includes €24,000 annual inventory costs, and leads to a

Table 1
Inventory Selection: (1) With MKS Transferium

	With MKS Transferium	
Number	Component	Value (€)
1	Twistlock	450
2	Luffing Bearing (Cyl)	3 500
3	Block Chain (Hook)	2 100
4	Control Module	4 200
5	Drive Unit Coupling	1 800
6	Rope Guard/Sheave	3 400
7	Oil Cooler Pump	4 800
8	Safety/Pressure Valve	3 600
9	Cargo Block	2 100
10	Check Valve/Hydr. (Cyl)	2 200
11	V-Pump (Main Pump)	8 400
12	Motor Swivel Gear	8 200
13	Cable Drum	5 100
Total:		49 850

Note: Components are visualized in Figures 6, 7 and 8 based on the number stated in the table

Table 2
Inventory Selection: (2) Only MKS Mercurius

	Only MKS Mercurius	
Number	Component	Value (€)
1	Twistlock	450
2	Luffing Bearing (Cyl)	3 500
3	Block Chain (Hook)	2 100
4	Control Module	4 200
5	Drive Unit Coupling	1 800
6	Rope Guard/Sheave	3 400
7	Oil Cooler Pump	4 800
8	Safety/Pressure Valve	3 600
9	Cargo Block	2 100
10	Check Valve/Hydr. (Cyl)	2 200
11	V-Pump (Main Pump)	8 400
12	Motor Swivel Gear	8 200
13	Cable Drum	5 100
14	Guide Roller	1 800
15	Force Measuring Strap	2 200
16	Lifting Cable/Rope	8 200
17	Steel Strip	180
18	Hoisting Winch	29 500
19	Oil Motor (Winch)	17 000
20	Elec. Safety Sensor	360
21	Suction Pipe	2 300
22	Double Gear (Control) Pump	4 100
23	Cable Guide	500
24	Height Adjustment Hydr. (Cabin)	2 240
25	Slewing Gear	5 100
26	Chain (CW)	4 800
27	Electric Motor (CW)	4 500
28	Oil Cooler	4 500
Total:		137 000

Note: Components are visualized in Figures 6, 7 and 8 based on the number stated in the table

reduction of expected annual failure costs of €79,000, which means the annual net benefit is equal to €55,000. As a result the investment is expected to be recouped in less than 3 years.

4 Conclusions

With the analysis presented in this paper a spare-part inventory is proposed and optimized to increase availability/reliability of MSG's container-crane vessel MKS Mercurius.

The results showed that the cost-optimizing level of inventory for (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure is ≈35%, and for (2) MKS Mercurius as MSG's single vessel the optimal level of inventory is ≈55%. Furthermore the results showed that inventory leads to a significant improvement in vessel availability/reliability. Essentially, the amount of components to store in inventory and the corresponding initial investment is a managerial decision for MSG. This requires a consideration for either a cost-minimizing inventory, or a larger inventory for which the probability of outliers regarding annual failure costs decreases.

Based on the analysis in this study it is recommended, for the current situation with two container-crane vessels operating in the same area, to invest in a set of 13 components. This inventory requires an initial investment of €50,000 and is likely to result in expected annual savings of €13,000. The investment has an expected return of 26% (first year), and can be recouped within a period of 4 years. Furthermore, direct availability of these spare-parts will lead to an improvement to vessel reliability. In case MSG decides to relocate (or sell) one of the container-crane vessels an extended spare-part inventory for the MKS Mercurius is regarded to lead to a vital improvement to vessel availability and the vessels operational result. In this case MSG should make a substantial investment (€137,000) on an extensive in-

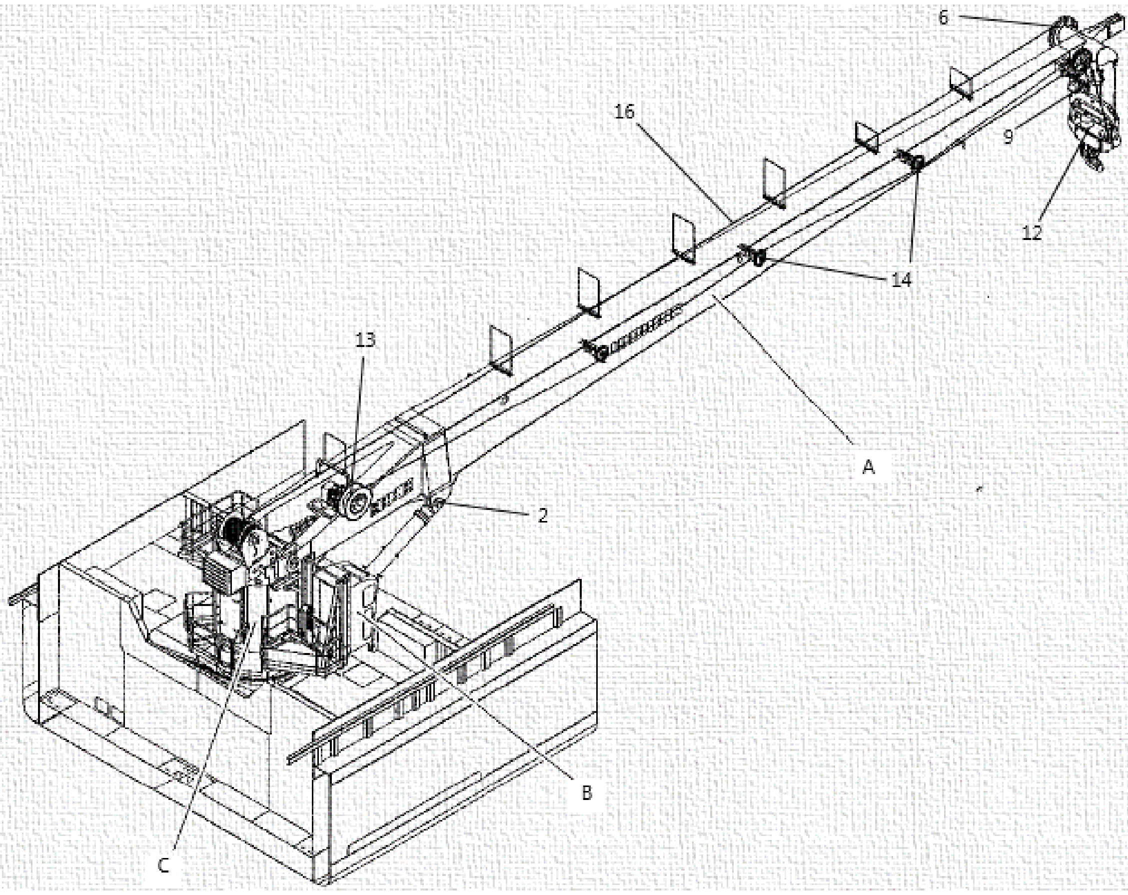

Fig. 6. General Arrangement External "Liebherr" Crane

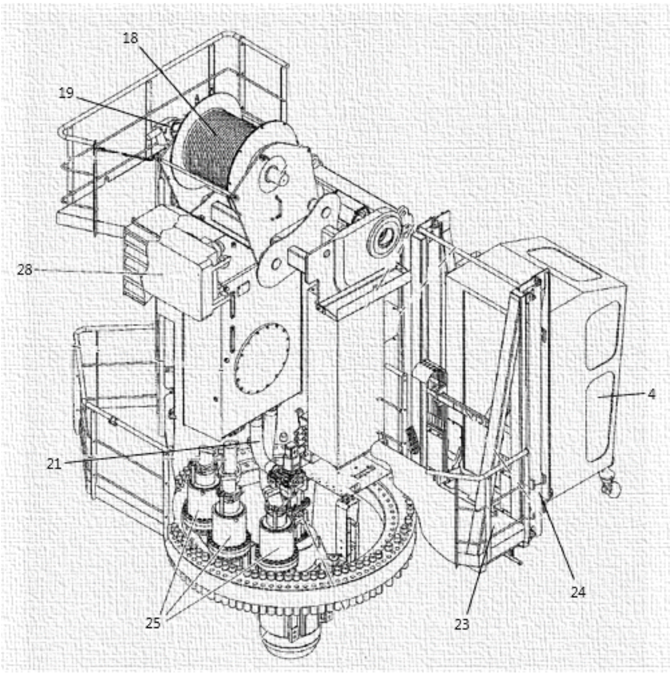

Fig. 7. Slewing Column "Liebherr" Crane

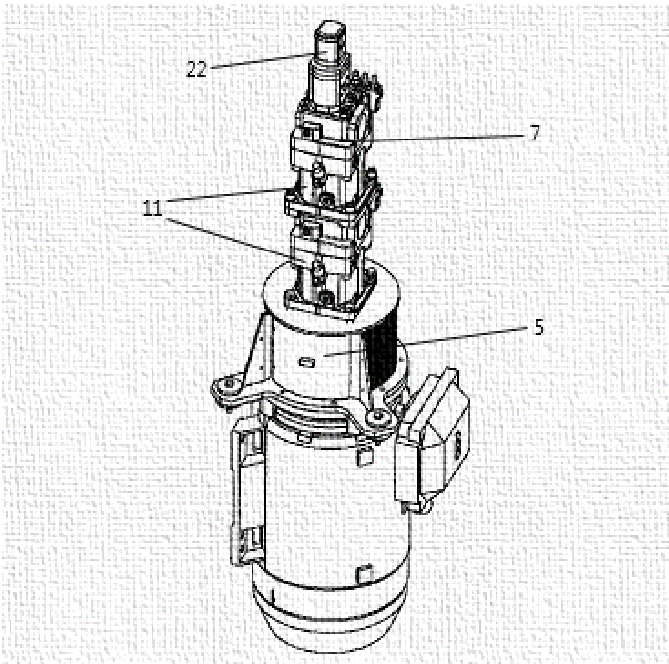

Fig. 8. Drive Unit "Liebherr" Crane

ventory (increase to 28 components).

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